

From Access to Capabilities: A Cluster Analysis of the Digital Divide across European Union Economies

Darya DANCAKOVÁ

<https://orcid.org/0000-0003-1621-6431>

Department of Banking and Investment

Faculty of Economics, Technical University of Košice, Slovakia

darya.dancakova@tuke.sk

Article's History

Received 15th of June, 2026; *Revised* 30th of July, 2026; *Accepted* 19th of August, 2026; *Available online:* 30th of September, 2026. *Published* as article in the Volume XXI, Fall, Issue 4(94), 2026.

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Suggested Citation

Dancaková, D. (2026). From Access to Capabilities: A Cluster Analysis of the Digital Divide across European Union Economies. *Journal of Applied Economic Sciences*, Volume XXI, Fall, 4(94), 1215 - 1240. [https://doi.org/10.57017/jaes.v21.4\(94\).07](https://doi.org/10.57017/jaes.v21.4(94).07)

Abstract

This study examines changes in the multidimensional profile of digital transformation across 22 European Union member states that are also OECD members, comparing two benchmark years 2017 and 2023. The proposed framework extends beyond digital access to include ICT human capital, innovation capacity, cybersecurity preparedness, and digital economic outcomes. Using data from Eurostat, the OECD, and the World Bank, the study applies k-means clustering, Partitioning Around Medoids (PAM), Principal Component Analysis, hierarchical clustering, and the Adjusted Rand Index to classify countries and assess changes over time.

Two clusters, catching-up and advanced, were identified in both years, although their composition changed. The catching-up cluster increased from 12 to 14 economies in 2023, with Estonia moving to the advanced cluster and Austria, Belgium, and France moving in the opposite direction. These transitions reflect relative repositioning rather than digital deterioration, as the advanced profile became increasingly associated with ICT skills, secure digital infrastructure, digital-service exports, and economic capacity. While connectivity gaps narrowed, disparities in skills, innovation, cybersecurity, and competitiveness persisted, suggesting partial convergence in digital access but continued divergence in digital capabilities.

Keywords: digital transformation, digital divide, digital capabilities, cluster analysis, cybersecurity readiness, European Union.

JEL Classification: C38; F15; O33; O47; O52.

Introduction

The rapid evolution of digital technologies has fundamentally reshaped the economic and social landscape across Europe. Accelerated by the COVID-19 pandemic, the European Union has largely secured basic connectivity, with nearly 94% internet penetration indicating noteworthy progress (Lobonț et al., 2025). Consequently, digital technologies have transformed the ways in which individuals work, communicate, and participate in economic activities.

In this context, cloud computing, Big Data, the Internet of Things (IoT), and artificial intelligence (AI) have emerged alongside established information and communication technologies (ICT) and e-commerce, revolutionising economic processes. Indeed, ICT and e-commerce have played a crucial role in the digitalisation of society by facilitating online communication, information exchange, and commercial transactions (Banerjee *et al.*, 2019). Furthermore, the sudden shift to virtual environments extended far beyond a short-term crisis response. Rather, it acted as a powerful catalyst, compressing years of digital transformation into a few months (Amankwah-Amoah *et al.*, 2021).

As a result, Member States are currently experiencing a profound digital revolution that is generating both significant opportunities and complex challenges at the individual, organisational, and societal levels (Bocean and Vărzaru, 2023). Moreover, ICT is widely regarded as a primary driver of economic growth within the European Union, contributing to GDP growth through enhanced productivity, innovation, and digital transformation (Fernández-Portillo *et al.*, 2020). Therefore, the European Union's Digital Decade policy seeks to promote territorial cohesion through the harmonisation of technological development across Member States. A central objective of this strategy is to enable individuals and businesses to acquire advanced digital skills and effectively leverage emerging technologies.

Nevertheless, beneath these encouraging signs of connectivity, a substantial and increasingly visible structural gap persists. Although the European Union aims to establish a cohesive digital landscape by 2030, evidence suggests that key drivers of digital innovation including advanced digital skills, AI adoption, and cloud computing remain concentrated in a relatively small number of established technological hubs. Consequently, an important paradox emerges. While digital access has become increasingly widespread, it remains unclear whether this apparent surface-level alignment masks deeper disparities in the capacity to utilise digital technologies productively and to generate economic value. Against this background, a critical question arises: does widespread digital access conceal a deeper divide in actual digital utility and economic power across European regions?

This study compares digital transformation profiles across two benchmark years, 2017 and 2023, to examine the structure of the digital divide. By identifying groups of countries with similar digital transformation characteristics, it explores how the European digital landscape changed before and after the period of accelerated digitalisation associated with the COVID-19 pandemic. Using a multidimensional, data-driven approach, the study evaluates the stability of these groups and differences in their characteristics to address the following research questions:

- RQ1: What structural patterns characterise the digital-transformation profiles of EU–OECD economies, and how do the identified clusters differ across the economic, connectivity, digital-skills, innovation, cybersecurity and digital-service dimensions in 2017 and 2023?
- RQ2: To what extent do the identified cluster structures indicate increasing similarity or persistent differences in digital transformation profiles across European countries?
- RQ3: What is the stability of the identified country clusters in the benchmark years 2017 and 2023, and which economies changed cluster membership between 2017 and 2023?

Exploring these questions, this study enhances our understanding of the evolving digital environment across selected EU and OECD member states and the challenges of reducing digital disparities. It also provides insights into how digital transformation aligns with the EU's goals of economic cohesion, innovation, and sustainable growth.

1. Literature Review

Investment in infrastructure has long been recognised as a fundamental driver of economic development and innovation, particularly in the fields of transportation and digital connectivity. Research and development (R&D) investment further strengthens this relationship by supporting knowledge creation, technological advancement, and regional competitiveness (Ma et al., 2026). Within the context of the digital economy, information and communication technology (ICT) infrastructure facilitates knowledge exchange, increases resource efficiency, lowers transaction costs, and stimulates both investment and productivity growth (Pradhan et al., 2017). Internet penetration has been identified as an important catalyst for economic expansion and innovation (Okolo et al., 2025), while investments in digital infrastructure, education, and training enable countries to better capture the benefits of technological progress (Vu, 2011).

Moreover, digital technologies, including broadband networks, mobile communication systems, cloud computing, artificial intelligence, and data-driven applications, have consequently become central components of contemporary economic development. Empirical evidence suggests that both fixed and mobile broadband positively influence firm productivity and economic performance, although the magnitude of these benefits depends not only on the availability of technology but also on how effectively it is utilised within organisations and societies (Haller and Lyons, 2015; Thompson and Garbacz, 2011).

Despite substantial advances in digital connectivity, significant disparities in access to digital technologies persist at the global level. While internet penetration exceeds 90% in many high-income economies, only around one-quarter of individuals in low-income countries were connected to the internet in 2022, leaving approximately 2.6 billion people excluded from the digital economy (International Telecommunication Union, 2023). Furthermore, nearly 850 million people worldwide lack a legal identity, limiting their ability to access digital public services, financial systems, and other forms of digital participation (Clark et al., 2023). These challenges have traditionally been associated with the first level of the digital divide, which primarily concerns inequalities in ICT access, broadband availability, and internet connectivity (Setthasuravich and Kato, 2020; Cariolle, 2021).

However, contemporary research suggests that the digital divide is considerably more complex than disparities in technological access alone (Lythreatis et al., 2022). As access to digital technologies has expanded, scholars have increasingly shifted their attention towards differences in digital skills, technological competencies, and the ability to effectively utilise digital resources. This evolution has given rise to the concept of the second-level digital divide, which refers to inequalities in digital capabilities, skills, technological literacy, and patterns of technology use arising from individual socio-economic and socio-demographic characteristics of users (Luo and Chea, 2018; Welser et al., 2019). From this perspective, access to ICT alone does not guarantee meaningful participation in the digital economy, nor does it support digital transformation, as individuals, firms, regions, and countries differ substantially in their capacity to exploit digital technologies.

Numerous studies have identified a range of socioeconomic and sociodemographic determinants that influence these inequalities, such as income, educational attainment, age, ethnicity, urbanisation, and individual characteristics (Goncalves et al., 2018; Hidalgo et al., 2020). Building on this foundation, the third-level digital divide addresses disparities in the outcomes and benefits resulting from digital technology use (Van Deursen and Helsper, 2015; Lythreatis et al., 2022).

Unlike the first level, which emphasises ICT access, and the second level, which centres on personal skills and capabilities for using digital technologies, the third level assesses whether digital engagement results in concrete economic and social benefits. These include productivity improvements, innovation outcomes, increased competitiveness, income growth, and wider enhancements in well-being for individuals and society overall. This highlights that digital transformation is mainly a human-centric endeavour rather than solely a technological change, emphasising the crucial role of human capital as the essential element a country should prioritise to bridge this gap. Human capital is the key mechanism by which digital access translates into digital capabilities and, ultimately, into economic outcomes (Qureshi, 2023; Zhang et al., 2025).

It is worth noting that within the European Union, substantial progress has been made in reducing many of the barriers associated with the first-level digital divide. The Digital Decade strategy explicitly identifies digital public services, electronic identification, and electronic health records as key pillars of a human-centred digital transformation. As a result, approximately 88% of central government services are already fully available online, indicating that many Member States have largely addressed the challenge of basic digital access. Nevertheless, significant challenges remain regarding resilience, technological sovereignty, and the creation of an inclusive digital environment capable of supporting innovation and long-term competitiveness (European Commission, 2023). This highlights that, although basic access is primarily an infrastructure issue, addressing these deeper systemic problems is fundamentally a human capital challenge (Grigorescu et al., 2021). Without developing a highly skilled and digitally literate workforce, advanced digital infrastructure cannot be fully utilised and remains strategically vulnerable (Kovac et al., 2024).

Recent evidence strongly supports this view. Digital skills are recognised as a major driver of enterprise productivity, enabling the adoption of Industry 4.0 technologies, artificial intelligence, advanced analytics, and data-driven decision-making. At the same time, more than 70% of European firms identify shortages of digital skills as a significant barrier to investment and technological adoption. Between 57.5% and 62.8% of enterprises attempting to recruit ICT specialists report difficulties in filling vacancies, while among large enterprises this figure exceeds 72% (Aleca and Mihai, 2025). Although approximately 10.3 million ICT specialists currently work within the European Union, representing around 5% of total employment, achieving the Digital Decade target of 20 million ICT specialists by 2030 would require recruitment rates far exceeding current trends (Eurostat, 2024).

Furthermore, substantial territorial disparities persist. Sweden (8.6%), Luxembourg (8.0%), and Finland (7.8%) record some of the highest shares of ICT specialists in employment, whereas Greece (2.5%) and Romania (2.8%) remain significantly below the EU average (Eurostat, 2024). Such differences suggest the emergence of a “two-speed Europe”, where advanced digital capabilities remain concentrated in a relatively small group of innovation leaders while other countries risk becoming predominantly consumers rather than creators of digital technologies. As Teigland and Wiberg (2025) argue, the shortage of highly skilled digital talent represents not only a labour-market challenge but also a strategic threat to European competitiveness, technological sovereignty, and long-term innovation capacity.

The increasing importance of human capital is further reinforced by the growing complexity of cybersecurity challenges (Salminen et al., 2020). As organisations, governments, and citizens become increasingly dependent on interconnected digital systems, the benefits of digitalisation are accompanied by greater exposure to cyber threats. The

widespread adoption of broadband networks, cloud computing, artificial intelligence, and digital public services simultaneously expands the potential attack surface, creating new vulnerabilities for firms and public institutions undergoing digital transformation (Gebremeskel et al., 2023). In this context, cybersecurity has evolved from a purely technical issue into a strategic prerequisite for sustainable digital development.

Literature suggests that cybersecurity capabilities are not distributed evenly across populations and territories but are strongly associated with digital skills, internet experience, and socioeconomic resources (Dodel and Mesch, 2018). Individuals and regions with greater digital engagement tend to exhibit stronger cybersecurity practices, whereas digitally disadvantaged groups face greater difficulties in acquiring the knowledge and skills necessary to protect themselves in digital environments. Consequently, cybersecurity can be viewed as a capital-enhancing capability that enables individuals and organisations to safely participate in digital activities and derive benefits from technological adoption. From the perspective of digital divide theory, this suggests that cybersecurity may act as an important mechanism linking second-level divides in digital skills and capabilities with third-level divides in economic and social outcomes. Countries may therefore display similar levels of connectivity while differing substantially in their ability to transform digital technologies into innovation, productivity, and economic value due to differences in cybersecurity readiness and digital resilience.

Recent studies increasingly recognise cybersecurity as a core component of digital transformation rather than merely a mechanism for protecting digital assets (Chotia et al., 2025). As organisations, governments, and societies become more dependent on cloud computing, artificial intelligence, big data analytics, and digital public services, the benefits of digitalisation increasingly depend on the security and resilience of underlying digital infrastructures. Inadequate cybersecurity can undermine digital transformation efforts through data breaches, operational disruptions, financial losses, and reduced trust in digital services, limiting the ability of organisations and economies to realise the full benefits of technological adoption (Chotia et al., 2025).

Cybersecurity is commonly defined as the set of measures implemented through ICT systems and networks to protect organisations and institutions from cyberattacks, data breaches, and disruptions of digital operations (Özsungur, 2021). At the national level, secure internet servers represent an important component of digital infrastructure, reflecting a country's capacity to support secure communications, protect sensitive information, and deliver reliable digital services. As such, they have increasingly been associated with effective digital governance, institutional credibility, and trust in digital environments (Makki and Khalife, 2026).

The growing importance of cybersecurity is also reflected in changing user behaviour. According to Eurostat (2026), 76.9% of EU internet users actively managed access to their personal information online, compared with 73.2% in 2023, indicating increasing awareness of cybersecurity and privacy risks. At the same time, investment in European data-centre infrastructure is projected to exceed USD 54 billion in 2025, driven by the growing demand for secure digital environments and AI-enabled applications requiring high-security data-processing capabilities. Nevertheless, considerable disparities persist across Member States. Countries such as Finland report some of the highest levels of digital security practices, whereas Romania remains among the weakest performers, suggesting that cybersecurity readiness is unevenly distributed across Europe.

These disparities have important implications for digital transformation. Countries with stronger cybersecurity capabilities are generally better positioned to support data-intensive innovation, AI deployment, and digital public services, whereas weaker cybersecurity environments may constrain the adoption and productive use of advanced digital technologies (Makki and Khalife, 2026; Chotia et al., 2025). Furthermore, the increasing integration of artificial intelligence into digital systems introduces a dual challenge. While AI enhances cybersecurity through improved threat detection and adaptive defence mechanisms, it can also be exploited to develop more sophisticated cyberattacks, increasing the complexity of the threat landscape (Nguyen Duc and Chirumamilla, 2019). Consequently, cybersecurity readiness is emerging as an important dimension of digital competitiveness and resilience, reinforcing the need to examine the broader factors shaping digital transformation beyond connectivity alone.

2. Research Methodology

This study aims to compare digital transformation across selected European countries that are also members of the OECD by identifying similarities and differences in their digital transformation profiles. The empirical framework adopts a multidimensional view of digital transformation based on digital divide theory and digital development literature. It emphasises that effective digital transformation depends on digital access, human capital, innovation, cybersecurity, and economic outcomes, not just the spread of digital technologies. Therefore, the chosen indicators reflect the main dimensions identified in earlier research as key factors for digital transformation and competitiveness (van Dijk, 2020; Lythreathis et al., 2022; Teigland and Wiberg, 2025).

The empirical analysis focuses on European Union member states that are also members of the Organisation for Economic Co-operation and Development (OECD). This sampling strategy combines the EU's regulatory framework with the homogeneous institutional and economic features of OECD economies, thereby reducing heterogeneity and improving cross-country comparisons of digital transformation. It aligns with the OECD's approach to analysing digital transformation across economies (OECD, 2020) and with previous empirical research on OECD European Union countries (Fernández-Portillo et al., 2020). The analysis uses publicly available data for 2017 and 2023 from Eurostat, OECD, and the World Bank. The final sample includes 22 countries with complete observations: Austria, Belgium, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, the Netherlands, Poland, Portugal, Slovakia, Slovenia, Spain, and Sweden. The remaining EU members, Bulgaria, Croatia, Cyprus, Malta, and Romania, were excluded for not meeting OECD membership requirements.

The selection of 2017 and 2023 as key comparison points was motivated by the COVID-19 pandemic's significant influence on digital growth across Europe. Earlier research often uses the period before the pandemic to evaluate digitalisation trends in European nations (Fidan, 2024). Before 2020, digital development in the European Union mainly involved slow, steady progress in connectivity, broadband infrastructure, and digital services. However, the COVID-19 pandemic acted as a major accelerator of digital transformation, substantially increasing the pace of digital technology adoption among firms, public institutions, and households. For instance, Gathmann et al. (2024) estimate that the pandemic accelerated technological adoption, particularly among organisations that had previously lagged in digitalisation. Comparing 2017's pre-pandemic environment with 2023's post-pandemic one

reveals whether this acceleration increased digital tech integration among European countries or reinforced existing disparities.

To operationalise the multidimensional nature of digital transformation, a set of indicators was selected to capture the principal dimensions identified in the literature. Internet use, household internet access, fixed broadband coverage, fixed broadband subscriptions, and mobile subscriptions represent the infrastructure and connectivity conditions associated with the first level of the digital divide. Employed ICT specialists capture the availability of advanced digital skills and human capital, reflecting a country's capacity to effectively utilise, manage, and develop digital technologies. This dimension is particularly relevant because recent EU evidence highlights the close relationship between digital transformation, ICT capabilities, and labour-market performance (Nicola-Gavrila et al., 2026).

Given the increasing importance of cybersecurity within digital transformation processes, the number of secure internet servers is included as an indicator of cybersecurity readiness and digital resilience. As discussed in the literature review, secure digital infrastructures support trusted digital interactions, facilitate digital governance, and contribute to the effective deployment of data-intensive technologies. Finally, ICT service exports and GDP per capita capture the economic outcomes associated with digital transformation. ICT service exports reflect the ability of national economies to generate value from knowledge-intensive digital activities and participate in international digital markets, while GDP per capita serves as a development indicator, representing the general level of economic progress and the wider economic effects of digitalisation. Table 1 presents the variables employed in the empirical analysis.

Given the complex nature of digital transformation, examining indicators alone can hide broader trends across European economies. Cluster analysis was used to identify groups of countries with similar profiles across selected dimensions, involving several steps in the process. Before cluster analysis, the Pearson correlation coefficient was computed on the raw, non-standardised data for each pair of variables. x_j and x_k .

$$r_{j,k} = \frac{Cov(x_j, x_k)}{\sigma_j \sigma_k} \quad (1)$$

When the correlation coefficient $r_{j,k}$ exceeded 0.90, one variable was removed to ensure that the remaining indicators represented distinct conceptual dimensions (Dormann et al., 2013).

Table 1: Variables Used in This Study

Variable	Unit	Shortcut	Source
GDP per capita	USD per capita	GDPpc	World Bank WDI
Internet use	% of population	IntUse	World Bank WDI
Employed ICT specialists	% of employed persons	ICTspec	Eurostat/DESI
Households with Internet access	% of households	HHnet	Eurostat/DESI
Fixed broadband coverage	% of households	FBCov	Eurostat/DESI
Mobile subscriptions	Number of subscriptions (per 100 people)	MobSubs	World Bank WDI
R&D expenditure	% of GDP	RDexp	OECD

Variable	Unit	Shortcut	Source
Fixed broadband subscriptions	Number of subscriptions (per 100 people)	FBSubs	World Bank WDI
ICT service exports	% of service exports	ICTexp	World Bank WDI
Secured Internet servers	Number of servers (per 1 million people)	SecSrv	World Bank WDI

Source: Author's elaboration.

In the next step, variables were standardised using z-scores based on means and standard deviations calculated from the combined 2017 and 2023 samples. Using the same parameters across both years in a single dataset prevented variables with larger scales from skewing distance measurements and maintained comparability over time (Raymaekers & Zamar, 2020):

$$z_{i,j} = \frac{x_{i,j} - \bar{x}_j}{\sigma_j} \quad (2)$$

where $\bar{x}_j$ is the mean and σ_j is the standard deviation of the variable.

The subsequent step involved selecting the number of clusters. The best cluster count (k) was found by combining internal validation indices and the silhouette method (Rousseeuw, 1987). For each observation i , the silhouette score $s(i)$ measures how appropriately the point belongs to its cluster compared to how well it is separated from other clusters. The silhouette value ranges from -1 to $+1$, with higher scores indicating a better fit.

$$s(i) = \frac{b(i) - a(i)}{\max\{a(i), b(i)\}} \quad (3)$$

Where $a(i)$ is the average distance between i and all points in its assigned cluster, and $b(i)$ is the minimum average distance between i and points in any other cluster.

Next, the mean silhouette index was computed for all observations to identify the optimal number of clusters (k) among all n observations.

$$\bar{s}(k) = \frac{1}{n} \sum_{i=1}^n s(i) \quad (4)$$

The analysis assessed the average silhouette coefficient for candidate solutions from $k=2$ to $k=8$. The lower bound ($k=2$) provides the smallest meaningful partition for comparing groups. In contrast, the upper bound ($k=8$) was adopted as a pragmatic limit beyond which the partition would become excessively granular for only 22 countries. The optimal number of clusters was identified as the value of k that maximised the average silhouette index. This approach balances model complexity and interpretability, making it highly recommended for exploratory multivariate analyses of socio-economic datasets (Rousseeuw, 1987; Kaufman & Rousseeuw, 1990; Kassambara, 2017).

To complement the silhouette approach, the NbClust Index Aggregator (Charrad et al., 2014) was employed to determine the optimal number of clusters (k) using a multi-index consensus method. This algorithm calculates more than 30 independent cluster validity indices, each assessing different aspects of intra-cluster compactness and inter-cluster separation and then selects the value of k most frequently recommended by these indices.

After establishing the optimal number of clusters through silhouette and consensus-based criteria, the analysis proceeded to the partitioning phase, in which two complementary clustering algorithms were applied to identify distinct groups of countries. The K-means algorithm (Hartigan & Wong, 1979) was used as a baseline method due to its computational efficiency and interpretability in minimising within-group variance.

$$\min_{C_1, \dots, C_k} \sum_{c=1}^k \sum_{i \in C_c} \|x_i - \mu_c\|^2 \quad (5)$$

where: x_i is the feature vector of country i , μ_c is the mean vector of cluster C_c and the $\|\cdot\|$ denotes the Euclidean norm.

In parallel, the Partitioning Around Medoids (PAM) algorithm (Kaufman and Rousseeuw, 1990) was implemented as a robust alternative that mitigates the influence of extreme or atypical observations by designating real data points as cluster centres (medoids) rather than mean centroids. The combined use of K-means and PAM enables a comparative validation of the resulting structures, ensuring both statistical soundness and robustness against outlier effects.

$$\min_{m_1, \dots, m_k} \sum_{c=1}^k \sum_{i \in C_c} d(x_i, m_c) \quad (6)$$

where: m_c is the medoid of cluster C_c and $d(x_i, m_c)$ is the Euclidean distance between them.

Since PAM uses actual observations instead of mean centroids, it is less affected by outliers and small-sample distortions, offering a stability check for the K-means outcomes.

To ensure the reproducibility of the clustering structure, bootstrap-based stability analysis following Hennig (2007) was performed, using the Jaccard similarity coefficient to quantify the consistency of country memberships across 300 resamples. Temporal comparability between the start- and final-year classifications was assessed using the Adjusted Rand Index (ARI) (Hubert and Arabie, 1985), which measures the agreement between partitions beyond random chance.

Between-cluster differences were assessed separately for each benchmark year using both one-way ANOVA and the Kruskal–Wallis test for every retained indicator. For each year, p-values from every test family were corrected across the nine indicators using the Benjamini–Hochberg method. Indicators with a significant adjusted Kruskal–Wallis result were subsequently examined using Dunn’s pairwise comparison with Benjamini–Hochberg adjustment (Dunn, 1964; Benjamini and Hochberg, 1995).

To facilitate interpretation and visualise multidimensional relationships among countries, Principal Component Analysis (PCA) was employed to project standardised features onto orthogonal axes representing the greatest variance (Jolliffe, 2011). Additionally, hierarchical clustering using Ward’s minimum variance method (Ward, 1963) was applied to reveal the nested structure of inter-country similarities through dendrograms. All computations, visualisations, and statistical tests were performed using R (version 4.5.1 RStudio).

3. Results and Discussion

3.1 Descriptive Statistics and Variables Selection

Table 2 presents descriptive statistics derived from the original, non-standardised pooled dataset, which encompasses all observations from the study period spanning 2017 and 2023.

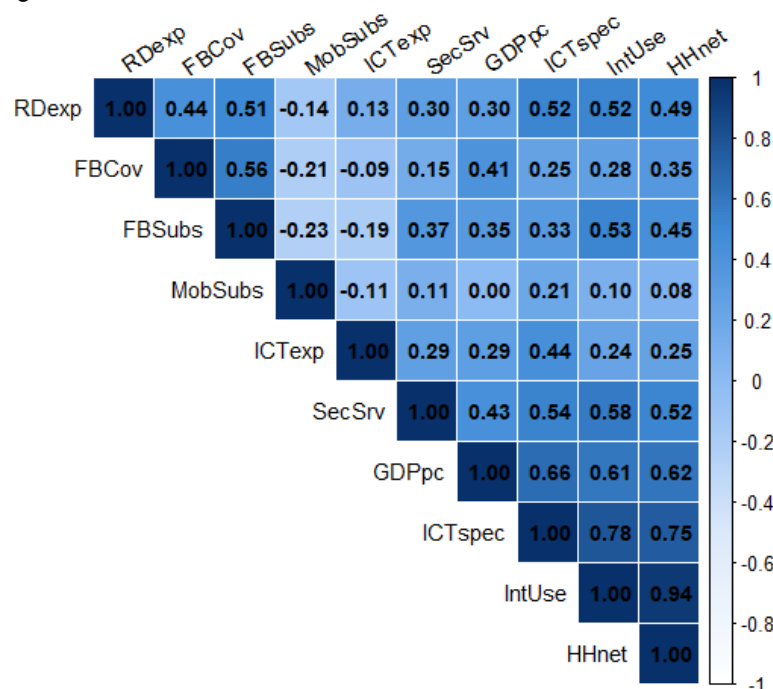
Table 2: Descriptive Statistics of Non-Standardised Raw Variables

Variable	Mean	SD	Min	Max
GDP per capita	41,571.56	25,550.07	13,913.34	128,678.19
Internet use	86.67	8.31	67.26	98.92
ICT specialists	4.67	1.51	2.00	8.70
Households with internet	89.66	6.88	70.96	99.06
Fixed broadband coverage	95.16	7.14	70.20	100.00
Mobile subscriptions	124.59	13.03	99.83	154.15
R&D expenditure	1.89	0.85	0.53	3.57
Fixed broadband subscriptions	34.85	6.76	19.95	48.67
ICT service exports	13.03	9.94	2.81	57.23
Secure internet servers	50,175.02	55,052.03	3,695.69	261,262.41

Source: Author's elaboration.

To assess potential multicollinearity, Pearson correlation coefficients were calculated using the same pooled raw dataset before standardisation, as shown in Figure 1.

Figure 1: Correlation Matrix of Non-Standardised Variables



Note: Pooled, unstandardised observations for 2017 and 2023 (N=44). Source: Own elaboration.

Figure 1 presents the Pearson correlation matrix for the pooled benchmark-year sample. Internet use and household internet access formed the only pair exceeding the exclusion threshold ($r=0.942$). Household internet access was therefore excluded, while Internet use was retained because it captures actual digital engagement and is more directly related to digital participation (van Dijk, 2020; Lythreathis et al., 2022).

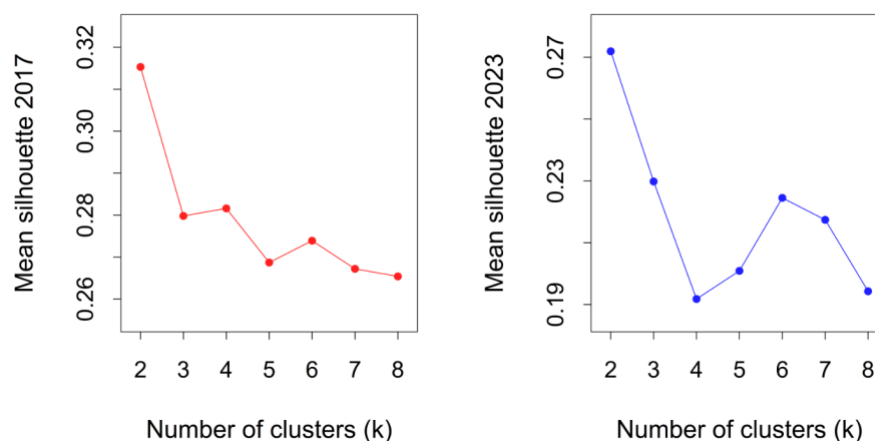
All remaining correlations were below the threshold. The strongest association among the retained indicators was between ICT specialists and Internet use ($r=0.785$), while the weakest was between mobile subscriptions and GDP per capita ($r=0.005$). Mobile and fixed-broadband subscriptions were also only weakly related ($r=-0.233$), confirming that they capture different forms of connectivity. Consequently, nine indicators were retained for the subsequent analyses: GDP per capita (GDPpc), Internet use (IntUse), ICT specialists (ICTspec), fixed-broadband coverage (FBCov), mobile subscriptions (MobSubs), R&D expenditure (RDexp), fixed-broadband subscriptions (FBSubs), ICT service exports (ICTexp), and secure internet servers (SecSrv).

3.2 Validation of the Clustering Procedure

The optimal number of clusters was assessed separately using average silhouette width and NbClust. Following the prespecified rule, the solution maximising cohesion and separation was selected (Rousseeuw, 1987), while NbClust provided complementary multi-index evidence (Charrad et al., 2014). As shown in Figure 2, ($k=2$) achieved the highest silhouette width in both 2017 (0.315) and 2023 (0.272). Both values exceeded 0.250, indicating modest but interpretable structure (Kaufman and Rousseeuw, 1990), although the lower 2023 value suggests a less distinct partition and greater uncertainty near the cluster boundary.

NbClust produced dispersed recommendations. In 2017, ($k=2$) received the greatest support (8 of 23 indices), coinciding with the silhouette solution. In 2023, ($k=8$) received the most votes (10 of 23), while ($k=2$) ranked second (4 of 23). Because ($k=8$) was the upper search boundary and implied fewer than three economies per cluster on average, NbClust was treated as complementary evidence and the final selection followed the prespecified maximum-silhouette criterion.

Figure 2: Average Silhouette Width by k in 2017 and 2023



Source: Author's elaboration.

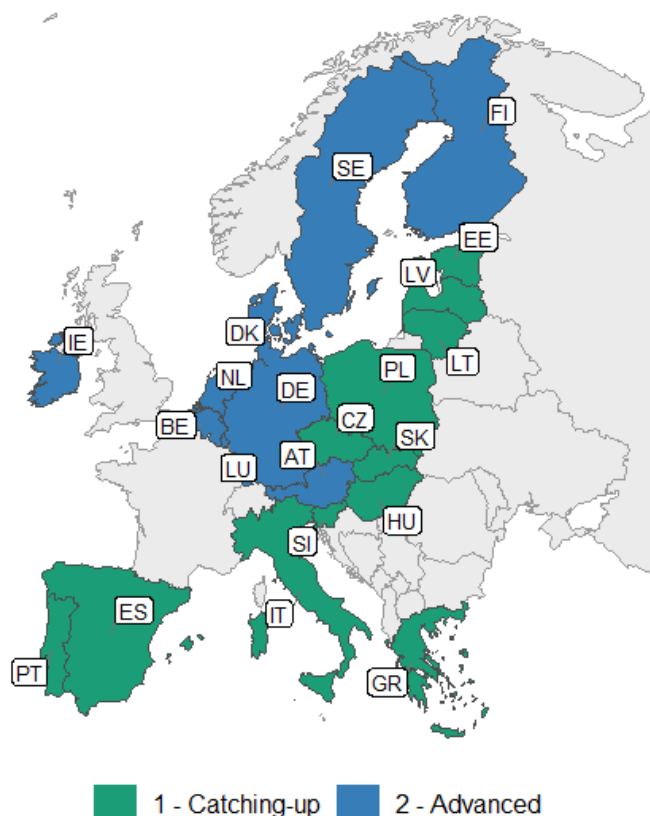
On this basis, the two-cluster solution was retained for both benchmark years. Its stability and robustness across clustering procedures were assessed through bootstrap resampling and PAM. The clusterisation Jaccard coefficients for K-means were 0.941 and 0.943 in 2017 and 0.829 and 0.778 in 2023; the corresponding PAM values were 0.854 and 0.792 in 2017 and 0.860 and 0.688 in 2023. All exceeded 0.60, indicating at least a recognisable structure (Hennig, 2007), although the second PAM cluster in 2023 was more sensitive to resampling. Agreement between the K-means and PAM assignments, measured separately for each benchmark year, was moderate in 2017 (ARI = 0.654) and strong in 2023 (ARI = 0.818). The methods classified Austria and Ireland differently in 2017 and Estonia differently in 2023.

3.3 Cluster Structures in 2017 and 2023

The cluster analysis shows that digital transformation in the EU-OECD economies from 2017 to 2023 experienced partial rather than full convergence. Two broad profiles were identified in both benchmark years: Cluster 1 (catching-up) and Cluster 2 (advanced). These labels describe relative multivariate positions rather than absolute rankings or uniformly superior performance across every indicator.

Figure 3 and Table 3 show that the 2017 catching-up cluster comprised 12 economies. Compared with the advanced cluster, it recorded lower GDP per capita (USD 20,355.13 versus USD 56,452.65), Internet use (76.04% versus 89.24%) and ICT-specialist employment (3.26% versus 5.05%), alongside weaker R&D expenditure, fixed-broadband penetration and secure-server density. Nevertheless, fixed-broadband coverage already averaged 90.74%, while mobile subscriptions exceeded the advanced-cluster mean (126.12 versus 119.28 per 100 people). The principal constraint was therefore not the absence of connectivity, but a weaker capacity to combine access with digital skills, innovation, secure infrastructure and economic value creation.

Figure 3: Spatial Distribution of Digital Transformation Clusters Across EU Countries in 2017



Source: Author's elaboration.

As reported in Table 5, after Benjamini–Hochberg adjustment, both ANOVA and the Kruskal–Wallis test identified significant between-cluster differences in GDP per capita, Internet use, ICT specialists, fixed-broadband coverage, R&D expenditure, fixed-broadband subscriptions and secure Internet servers. Mobile subscriptions and ICT-service exports were non-significant under both procedures. Dunn's pairwise comparisons confirmed significant differences between clusters for the same seven indicators (Table 6). The 2017 clusters therefore differed in economic capacity, effective Internet use, digital skills, innovation, fixed connectivity and secure infrastructure.

Table 3: Average Values of Digital Transformation Indicators by Cluster in 2017 and 2023

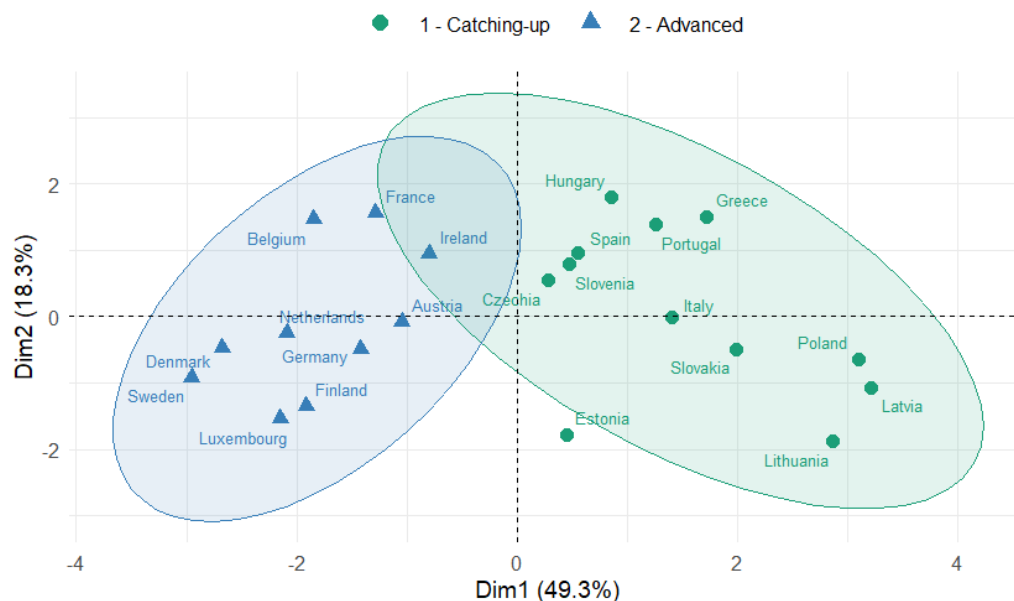
Variable (Unit)	2017 Cluster 1	2017 Cluster 2	2023 Cluster 1	2023 Cluster 2
GDP per capita (USD per capita)	20,355.13	56,452.65	32,989.27	69,813.87
Internet use (% of population)	76.04	89.24	89.03	95.25
ICT specialists (% of employment)	3.26	5.05	4.35	6.86
Fixed broadband coverage (% of households)	90.74	98.69	95.46	96.83
Mobile subscriptions (per 100 people)	126.12	119.28	123.27	131.23
R&D expenditure (% of GDP)	1.21	2.46	1.76	2.41
Fixed broadband subscriptions (number of subscriptions per 100 people)	29.28	37.07	35.50	39.28
ICT service exports (% of service exports)	9.05	14.17	11.33	20.53
Secure internet servers (number of servers per 1 million people)	13,126.80	29,629.76	44,870.01	140,712.70

Source: Author's elaboration.

Figure 4 provides complementary PCA evidence. The first and second principal components (PC1 and PC2) account for 49.28% and 18.34% of the variance, respectively, totalling 67.62%. Because component orientation is arbitrary, interpretation focuses on the relative magnitudes and sign patterns of the loadings (Jolliffe, 2011). The values in parentheses are PCA loadings, which indicate the weight and direction of each standardised indicator within a component; larger absolute values denote stronger contributions, while the signs show whether indicators load in the same or opposite directions. Because component orientation is arbitrary, a negative loading does not imply an adverse effect. PC1 was defined mainly by Internet use (-0.458), R&D expenditure (-0.425) and fixed-broadband coverage (-0.421), with ICT specialists, GDP per capita and fixed-broadband subscriptions loading in the same direction at approximately (-0.360). PC2 was dominated by mobile subscriptions (-0.780), indicating a distinct telecommunications dimension.

The country-level profiles show that digital leadership was already multidimensional in 2017. Sweden combined ICT specialists representing 6.60% of employment with R&D expenditure of 3.39% of GDP, while Finland recorded the highest ICT-specialist share (6.70%) and ICT-service exports of 27.13%. Denmark and the Netherlands combined high Internet use (95.32% and 94.36%) with fixed-broadband subscription rates above 42 per 100 people; the Netherlands also recorded the highest secure-server density, at 70,412.13 per million people. Luxembourg combined exceptional GDP per capita (USD 110,193.21) with 96.40% Internet use and complete broadband coverage, although its R&D expenditure (1.24%) and ICT-service exports (4.29%) were comparatively modest. Among the catching-up economies, Greece recorded the lowest Internet use (67.26%) and ICT employment (2.00%), Latvia the lowest broadband coverage (70.20%) and R&D intensity (0.53%), and Poland the lowest GDP per capita (USD 13,913.34) and fixed-broadband penetration (19.95 per 100 people). Estonia combined relatively strong ICT employment (5.30%) and secure-server density (29,131.22 per million people) with lower GDP per capita (USD 20,851.52) and R&D expenditure (1.25%), explaining its position near the cluster boundary.

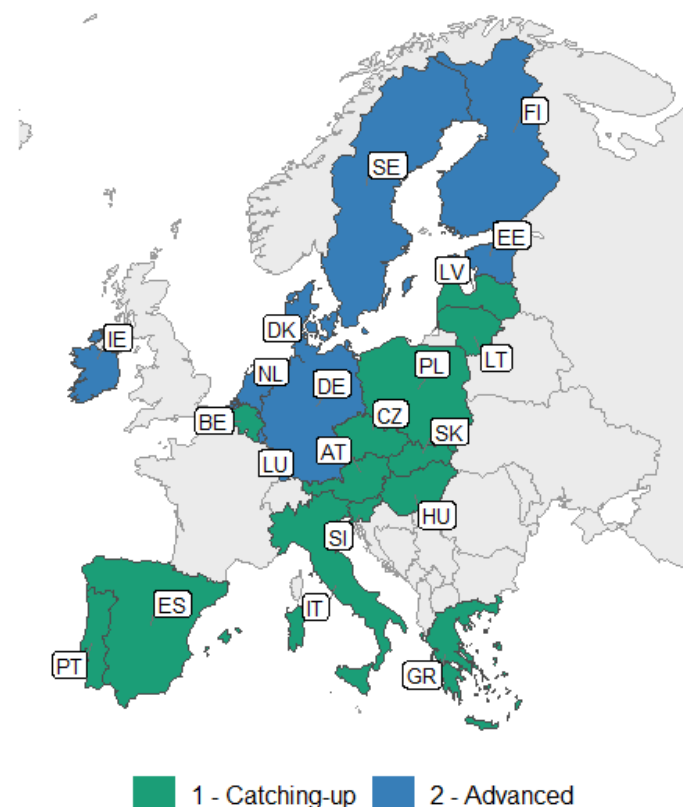
Figure 4: Principal Component Representation of Digital Transformation Clusters In 2017



Source: Own elaboration.

Figure 5 presents the spatial distribution of the 2023 clusters. The catching-up cluster had expanded to 14 economies, while the advanced cluster contained eight countries. The corresponding averages in Table 3 show that access differences had narrowed. The fixed-broadband coverage gap declined to 1.37 percentage points, while fixed-broadband subscriptions averaged 35.50 and 39.28 per 100 people in the catching-up and advanced clusters, respectively. Internet use also became more similar, reaching 89.03% and 95.25%.

Figure 5: Spatial Distribution of Digital Transformation Clusters Across EU Countries in 2023

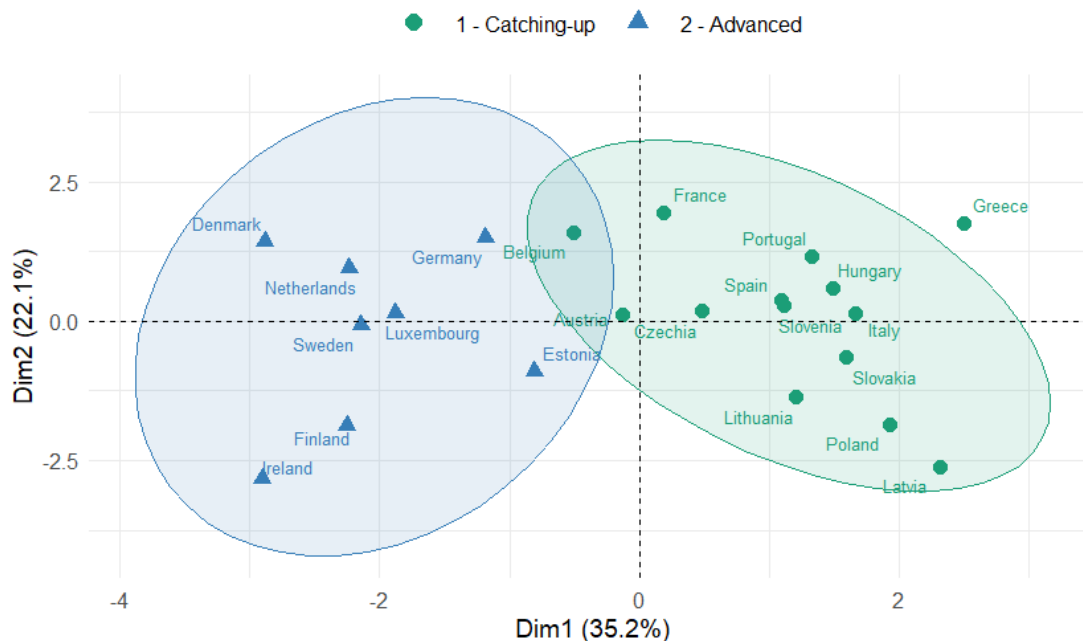


Source: Author's elaboration.

By 2023, both ANOVA and the Kruskal–Wallis test identified significant between-cluster differences only in GDP per capita, Internet use, ICT specialists and secure Internet servers (Table 5). Fixed-broadband coverage, mobile subscriptions, R&D expenditure, fixed-broadband subscriptions and ICT-service exports were non-significant under both procedures. Dunn’s pairwise comparisons confirmed significant cluster differences for the same four indicators (see Table 6). Statistical differentiation was therefore concentrated in economic capacity, effective Internet use, digital human capital and cybersecurity-related infrastructure.

Figure 6 presents the 2023 PCA results. The PC1 and PC2 explained 35.22% and 22.12% of the variance, respectively, for a total of 57.34%. PC1 was defined mainly by secure Internet servers (-0.496), ICT specialists (-0.475) and GDP per capita (-0.467), with smaller contributions from R&D expenditure (-0.326) and ICT-service exports (-0.287). Their common direction identifies PC1 as a combined dimension of digital capability and economic capacity. PC2 contrasted fixed-broadband subscriptions (0.589) and coverage (0.460) with ICT-service exports (-0.568), distinguishing infrastructure intensity from digital-service specialisation. Overall, the PCA results indicate that the 2017 divide was structured mainly around a broad access-and-development dimension, whereas the 2023 divide was more explicitly organised around human capital, economic capacity, secure infrastructure and the commercial exploitation of digital technologies. This finding is consistent with the argument that the digital divide increasingly concerns differences in capabilities and outcomes rather than physical access alone (van Dijk, 2020; Lythreathis et al., 2022; Gomes and Dias, 2025).

Figure 6: Principal Component Representation of Digital Transformation Clusters in 2023



Source: Author's elaboration.

The 2023 profiles reveal substantial progress in both groups. Nevertheless, the nature of the remaining divide changed. The difference in fixed-broadband coverage narrowed to only 1.37%, with averages of 95.46% in Cluster 1 and 96.83% in Cluster 2. The difference in Internet use also declined, although it remained evident at 89.03% compared with 95.25%. Fixed-broadband subscriptions reached 35.50 per 100 people in the catching-up cluster and 39.28 in the advanced cluster. These results indicate that basic digital access became considerably more similar across the two groups.

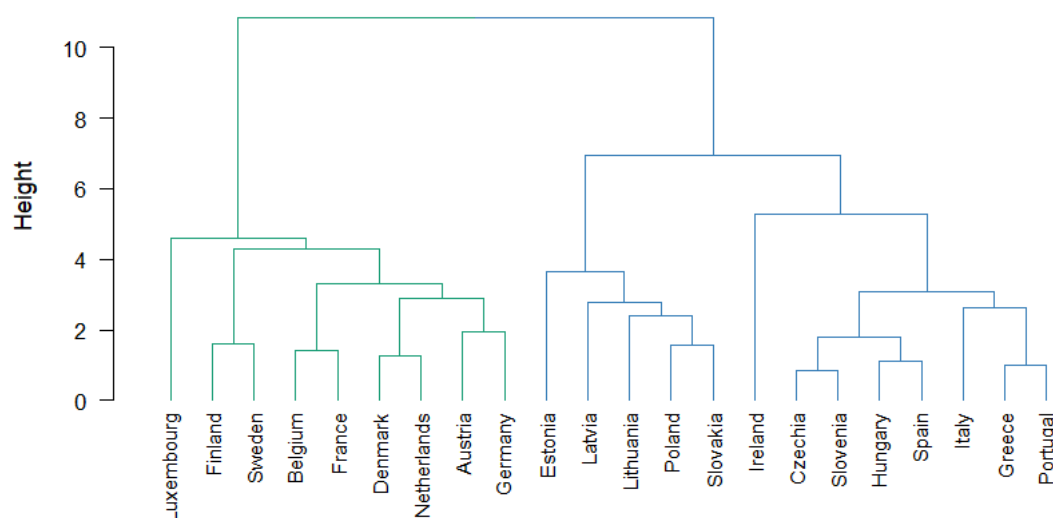
However, much larger differences remained in indicators capturing advanced digital capabilities. The advanced cluster recorded GDP per capita of USD 69,813.87, compared with USD 32,989.27 in the catching-up cluster. ICT specialists represented 6.86% of employment in the advanced cluster but only 4.35% in Cluster 1. ICT service exports reached 20.53%, compared with 11.33%, while secure Internet server density was 140,712.70 per million people in the advanced cluster and 44,870.01 in the catching-up group. Secure server density was therefore more than three times higher in the advanced cluster. This difference suggests that cybersecurity readiness, secure hosting capacity and the infrastructure supporting trusted digital transactions had become central elements of the contemporary divide. Similarly, the ICT-specialist gap indicates that the ability to deploy, manage and commercialise advanced technologies depended increasingly on specialised human capital.

Moreover, the 2023 country profiles show that the advanced economies followed different development models. Ireland combined GDP per capita of USD 103,887.80 with ICT-service exports of 57.23%, whereas Luxembourg recorded the highest GDP per capita (USD 128,678.19) and ICT specialists representing 8.00% of employment but ICT-service exports of only 3.94%. Denmark recorded the highest secure-server density (261,262.41 per million people), while the Netherlands combined secure-server density of 194,962.87 with the highest Internet-use rate (98.92%). Sweden recorded the highest ICT-specialist share (8.70%) and R&D intensity (3.57%), while Finland combined ICT specialists representing 7.60% of employment with ICT-service exports of 30.94%.

Among the catching-up economies in 2023, Greece continued to record the lowest ICT-specialist share (2.40%) and ICT-service exports (2.81%). Latvia increased Internet use from 78.47% to 91.50%, but broadband coverage remained at 74.00% and R&D expenditure at 0.83% of GDP. Poland's GDP per capita reached USD 22,056.67, while fixed-broadband subscriptions remained the lowest in the sample at 24.53 per 100 people. These contrasting country profiles demonstrate that neither the advanced nor the catching-up cluster represents a uniform development path.

The hierarchical clustering structures presented in Figures 7 and Figure 8 further validates the identified patterns. They provide complementary evidence of country proximity but were not used as an independent criterion for cluster membership.

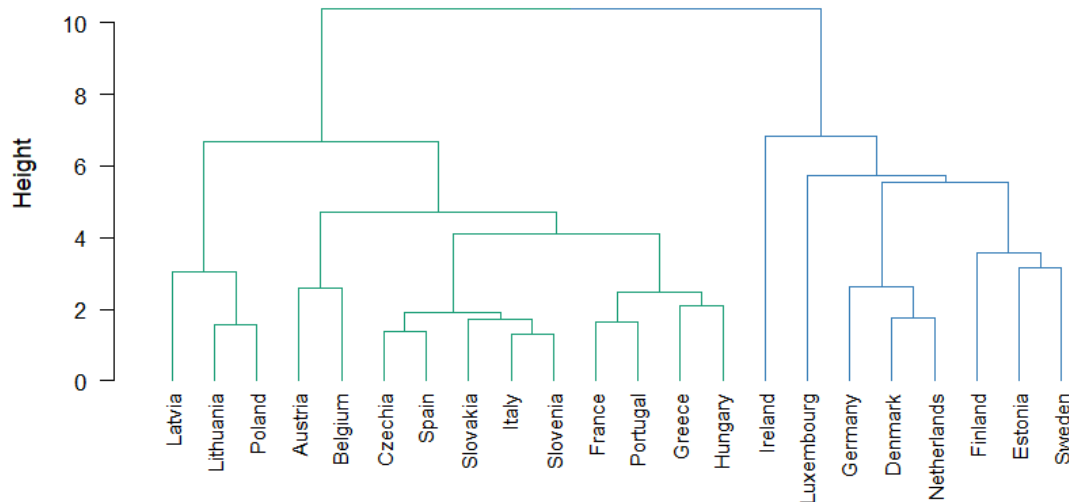
Figure 7: Hierarchical Clustering Structure of EU Member States in 2017



Source: Author's elaboration.

Table 4 identifies four changes in membership. Estonia moved from the catching-up to the advanced cluster, whereas Austria, Belgium and France moved in the opposite direction. The remaining 18 countries retained their classification. The corresponding ARI of 0.377 indicates moderate rather than high correspondence between the two benchmark-year partitions.

Figure 8: Hierarchical clustering structure of EU Member States in 2023



Source: Own elaboration.

Estonia's reclassification was associated with ICT specialists reaching 6.70% of employment, ICT-service exports 23.46%, complete broadband coverage and secure-server density of 112,224.02 per million people. Its advanced classification was therefore supported by strong digital capabilities despite GDP per capita of USD 30,133.30, substantially below the advanced-cluster average of USD 69,813.87. Austria and Belgium retained high R&D expenditure (3.29% and 3.32% of GDP) and almost universal broadband coverage (99.20% and 100.00%), but their ICT-specialist shares (5.30% and 5.40%), ICT-service exports (12.69% and 14.16%) and secure-server densities (42,281.00 and 33,664.59 per million people) remained below the corresponding advanced-cluster averages. France achieved complete broadband coverage and the highest fixed-broadband subscription rate in the sample (48.67 per 100 people), but recorded ICT specialists representing 4.70% of employment, ICT-service exports of 7.59% and secure-server density of 52,017.99 per million people. Their reassignment therefore reflects relative capability gaps rather than economic or digital deterioration.

Table 4: Changes in Cluster Membership Between 2017 and 2023

Country	Country Code	Cluster 2017	Profile 2017	Cluster 2023	Profile 2023
Austria	AT	2	Advanced	1	Catching-up
Belgium	BE	2	Advanced	1	Catching-up
Czechia	CZ	1	Catching-up	1	Catching-up
Denmark	DK	2	Advanced	2	Advanced
Estonia	EE	1	Catching-up	2	Advanced
Finland	FI	2	Advanced	2	Advanced
France	FR	2	Advanced	1	Catching-up
Germany	DE	2	Advanced	2	Advanced

Country	Country Code	Cluster 2017	Profile 2017	Cluster 2023	Profile 2023
Greece	GR	1	Catching-up	1	Catching-up
Hungary	HU	1	Catching-up	1	Catching-up
Ireland	IE	2	Advanced	2	Advanced
Italy	IT	1	Catching-up	1	Catching-up
Latvia	LV	1	Catching-up	1	Catching-up
Lithuania	LT	1	Catching-up	1	Catching-up
Luxembourg	LU	2	Advanced	2	Advanced
Netherlands	NL	2	Advanced	2	Advanced
Poland	PL	1	Catching-up	1	Catching-up
Portugal	PT	1	Catching-up	1	Catching-up
Slovakia	SK	1	Catching-up	1	Catching-up
Slovenia	SI	1	Catching-up	1	Catching-up
Spain	ES	1	Catching-up	1	Catching-up
Sweden	SE	2	Advanced	2	Advanced

Source: Author's elaboration.

These patterns are consistent with partial convergence in access rather than complete digital convergence. Connectivity became more similar, while differences persisted in ICT skills, cybersecurity readiness, digital value creation and economic capacity. This supports capability-based accounts of digital inequality, according to which comparable access can coexist with unequal capacities to convert digital technologies into productivity and innovation (van Dijk, 2020; Lythreathis et al., 2022; Gomes and Dias, 2025). Since cluster analysis doesn't assess beta or sigma convergence, these results are descriptive, suggesting partial convergence rather than providing definitive proof of a convergence process.

Conclusion

This study compared multidimensional digital-transformation profiles across 22 EU-OECD economies in 2017 and 2023. Two broad profiles, a catching-up cluster and an advanced cluster, were identified in both benchmark years, but their composition changed. Estonia moved into the advanced cluster, whereas Austria, Belgium and France moved into the catching-up cluster. These transitions do not represent straightforward digital progress or deterioration. They reflect relative repositioning as the advanced profile became increasingly defined by ICT human capital, secure digital infrastructure, digital-service exports and economic capacity.

The findings show that the European digital divide is changing rather than disappearing. Differences in internet use and broadband availability narrowed, providing evidence consistent with partial convergence in digital access. However, substantial disparities remained in countries' ability to convert connectivity into productive and internationally competitive digital activity. The expansion of the catching-up cluster from 12 to 14 economies and the weaker separation between the clusters in 2023 indicate an increasingly heterogeneous digital landscape. The remaining divide is therefore less about access alone and more about digital skills, innovation capacity, cybersecurity readiness and participation in international digital-service markets. As the study does not formally test beta or sigma convergence, these findings should be interpreted as descriptive evidence consistent with partial convergence.

The policy implication is clear: infrastructure remains necessary, but it is no longer sufficient. Achieving the objectives of the European Digital Decade requires greater emphasis on advanced digital skills, the development and retention of ICT specialists, cybersecurity capacity, business adoption of emerging technologies and the commercial application of research and development. Policies should also strengthen firms' participation in international digital-service markets and their ability to transform technological adoption into productivity and innovation. The relative repositioning of several economically developed countries demonstrates that strong connectivity or research performance in isolation does not guarantee a position at the digital frontier.

Several limitations should be acknowledged. The comparison of two benchmark years does not capture annual developments or short-term changes during the intervening period. Restricting the analysis to 22 EU–OECD economies limits the generalisability of the findings to the five EU economies outside this sampling frame. Although the revised indicators account for population size, the analysis does not directly measure artificial intelligence, cloud computing, platform activity, business digitalisation or digital public services. Cluster analysis is also exploratory: it identifies similarities among country profiles but does not establish causal relationships between digital transformation and economic performance. The lower stability of some clusters further suggests that countries near the boundary should be regarded as transitional cases rather than permanently assigned categories.

Future research should use annual panel data to examine the dynamics and determinants of digital convergence. Econometric analysis could identify how ICT skills, artificial-intelligence adoption, innovation systems, institutional quality, business digitalisation and public investment influence movements between digital profiles. Comparisons with non-European economies could also determine whether the capability-based divide observed in Europe represents a regional pattern or a broader transformation of the global digital economy. Overall, Europe is narrowing the digital-access gap faster than the digital-capability gap. Future convergence will therefore depend less on connecting economies and more on enabling them to transform connectivity into innovation, productivity and sustainable economic value.

CRedit Authorship Contribution Statement

Dancaková, D.: Responsible for conceptualising, developing methodology, curating data, performing formal analysis, conducting investigations, managing software, validating results, creating visualisations, and handling the original draft writing as well as review and editing.

Acknowledgments

During the preparation of this manuscript, the authors used Grammarly solely to improve language, grammar, spelling, punctuation, and readability. The tool did not replace the authors' intellectual contribution and was not used to generate scientific content, conduct the analysis, interpret the findings, or formulate the conclusions.

Funding

This paper is the output of a research project supported by the MINEDU of the Slovak Republic [grant No. 1/0638/25].

Conflict of Interest Statement

The authors state that no commercial or financial conflicts influenced the research.

Data Availability Statement

The data for this study were sourced from publicly accessible platforms such as Eurostat, the OECD Data Explorer, and the World Bank Open Data. The assembled dataset for the cluster analysis, along with the R scripts used for statistical analysis and figure creation, can be obtained from the corresponding author upon reasonable request. All original data continue to be publicly available via the respective providers.

Ethical Approval Statement

This study used only anonymised, aggregated secondary data from publicly accessible international sources such as Eurostat, the OECD Data Explorer, and the World Bank Open Data platform. No human participants, personal data, animals, surveys, interviews, or experiments were involved. Consequently, ethical approval and informed consent were not necessary. The research adhered to ethical principles of scientific investigation, and all data usage complied with the providers' terms and conditions.

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ANNEX 1

Table 5: ANOVA and Kruskal-Wallis results

Variable	ANOVA			Kruskal-Wallis		
	F (df = 1)	p	p (BH)	H (df = 1)	p	p (BH)
Benchmark year 2017						
GDP per capita	32.790	<0.001	<0.001***	15.652	<0.001	<0.001***
Internet use	28.722	<0.001	<0.001***	12.213	<0.001	0.002**
ICT specialists	21.571	<0.001	<0.001***	11.412	<0.001	0.002**
Fixed-broadband coverage	7.961	0.011	0.016*	9.210	0.002	0.004**
Mobile subscriptions	1.334	0.262	0.262	0.526	0.468	0.527
R&D expenditure	25.762	<0.001	<0.001***	10.017	0.002	0.003**
Fixed-broadband subscriptions	13.713	0.001	0.003**	7.670	0.006	0.008**
ICT-service exports	2.451	0.133	0.150	0.352	0.553	0.553
Secure Internet servers	6.907	0.016	0.021*	5.635	0.018	0.023*
Benchmark year 2023						
GDP per capita	15.857	<0.001	0.002**	9.019	0.003	0.006**
Internet use	18.092	<0.001	0.001**	10.296	0.001	0.004**
ICT specialists	37.513	<0.001	<0.001***	13.364	<0.001	0.002**
Fixed-broadband coverage	0.200	0.659	0.659	0.199	0.655	0.655
Mobile subscriptions	2.313	0.144	0.185	1.682	0.195	0.250
R&D expenditure	3.315	0.084	0.125	2.466	0.116	0.209
Fixed-broadband subscriptions	1.625	0.217	0.244	1.682	0.195	0.250
ICT-service exports	3.607	0.072	0.125	1.193	0.275	0.309
Secure Internet servers	23.764	<0.001	<0.001***	11.185	<0.001	0.004**

Note: All tests used 1 degree of freedom. BH = Benjamini-Hochberg adjustment. Significance stars refer to BH-adjusted p-values: * p < 0.050; ** p < 0.010; *** p < 0.001.

Source: Author's elaboration

Table 6: Dunn pairwise comparisons results following Significant Kruskal–Wallis Tests

Year	Indicator	Comparison	Dunn z	Adjusted p
2017	GDPpc	Cluster 1–Cluster 2	3.956	< 0.001***
2017	IntUse	Cluster 1–Cluster 2	3.495	< 0.001***
2017	ICTspec	Cluster 1–Cluster 2	3.378	< 0.001***
2017	FBCov	Cluster 1–Cluster 2	3.035	0.002**
2017	RDexp	Cluster 1–Cluster 2	3.165	0.002**
2017	FBSubs	Cluster 1–Cluster 2	2.769	0.006**
2017	SecSrv	Cluster 1–Cluster 2	2.374	0.018*

Year	Indicator	Comparison	Dunn z	Adjusted <i>p</i>
2023	GDPpc	Cluster 1–Cluster 2	3.003	0.003**
2023	IntUse	Cluster 1–Cluster 2	3.209	0.001**
2023	ICTspec	Cluster 1–Cluster 2	3.656	< 0.001***
2023	SecSrv	Cluster 1–Cluster 2	3.344	< 0.001***

Note: With two clusters, each Dunn procedure contains a single Cluster 1–Cluster 2 comparison. *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

Source: Author's elaboration